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Evaluation of Short Cut Gradation Test Procedures

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EVALUATION OF SHORT CUT GRADATION TEST PROCEDURES

INTRODUCTION

Aggregate gradation control is an essential ingredient in highway construction. In a typical year, the Ministry's construction staff performs some 6,500 gradation tests for acceptance of granular base and subbase aggregates alone (1). At the estimated cost of $50.00 per test, the total yearly expenditure would amount to $325,000.00. This figure does not include the financial resources required for gradation testing of bituminous and concrete aggregates.

More often than not, the Ministry's acceptance tests are also used by the supplier for production control purposes. Current gradation testing procedures require about two to three hours of time. This time span results in a somewhat inefficient production control since up to three hours of out of specification material could be produced and/or placed on a contract before the deviation is detected and corrective measures taken. This, of course, adds to the final cost.

In light of today's economic environment and in view of the time lag factor, the Soils and Aggregates Section embarked on a laboratory study of "short cut" gradation test procedures that could be used for acceptance testing. The objective of the study was to evaluate the potential for the short cut test methods on the basis of reduced testing time, economics, accuracy and precision of the test results. Other studies have shown that testing contributes about 13% towards the overall variability in test results. Sampling contributes 15% and the remainder is due to material variability caused by changes in source, handling, loading, transporting, etc.

The study concentrated on three short cut methods that are currently in use in North America and show promise as substitutes for the standard gradation test. The Ministry's existing procedure was also evaluated for information and comparison purposes.

DESCRIPTION OF TEST PROCEDURES

M.T.C. Test Procedures

The Ministry method for gradation testing is contained in M.T.C. Laboratory Procedure 602, Method of Test for Sieve Analysis of Fine and Coarse Aggregates. For construction field testing purposes, LS-602 is modified slightly (See Appendix A) to suit the equipment and needs of construction testing. Basically the procedure requires drying of the aggregate to a constant mass and sieving through the required sieves. The percentage smaller than 75 µm is determined by washing the fine aggregate portion (pass 4.75 mm) and drying to a constant mass.

Short Cut Test Procedures

The short cut gradation test methods chosen for evaluation are described in the FHWA report entitled Present Aggregate Gradation Control Practices and Alternative Test Methods (2). Three test procedures, which appear to offer significant benefits to the Ministry were chosen for evaluation. The test methods examined are outlined briefly below.

1. *Kentucky Method of Test for Percentage of Material Finer than a 75 µm (No. 200) sieve by Use of a Pycnometer.* By means of a pycnometer (jar fitted with a special lid, See Figure 1) and a weighing device, it is possible to determine the pass 75 µm percentage without drying the aggregate. For this procedure, a 4 kg test portion is placed into the pycnometer and water is added to the fill line. After the mass is determined, the sample is washed by decanting until the water is clear. The pycnometer is again filled and the mass determined. The mass of the pycnometer filled with water alone is also determined. By use of the recorded data and a simple formula, the percentage passing the 75 µm sieve is calculated.

2. *Gap Sieve Method (One Sieve Method).* In this method the aggregate is sieved through one critical sieve to determine the percentage by mass passing the sieve.

FIGURE 1

PHOTOGRAPH OF PYCNOMETER APPARATUS

3. *Iowa Method of Test for Sieve Analysis of Coarse Aggregate (Quick Method)*. This procedure requires sieving the aggregate through the coarse aggregate sieves down to and including the 4.75 mm.

It should be noted for both the Gap Sieving Method and the Coarse Aggregate Sieving Method that a determination of the percentage passing the 75 µm sieve is not made. Only the pycnometer test method allows the determination of this parameter. Given the importance of this parameter in our acceptance procedure, it is felt that test procedures that did not evaluate the pass 75 µm fraction would be of little benefit. Accordingly the test procedures for the Gap Sieving Method and the Coarse Aggregate Sieving Method were combined with the Pycnometer Method. These combined procedures only were evaluated during the project. Full descriptions of these combined methods are given in Appendix A.

Complete Wash Test

The complete wash test, while not a short cut method, was used for control purposes. It is recognized that there are some inaccuracies in the Gap Sieving and Coarse Aggregate Sieve Methods but comparison of these methods with the M.T.C. procedure would be somewhat fallacious since there may be inaccuracies in our own procedures.

For the complete wash test, the test portion is dried to a constant mass and then weighed. The material smaller than 75 µm is then removed by washing the entire test portion and decanting wash water over a 75 µm sieve until the water is clear. The particles retained on the 75 µm sieve are returned to the test portion which is then dried to a constant mass and weighed. Sieving the entire test portion through the coarse and fine aggregate sieves is accomplished in increments depending on the test portion size. Weighing the mass retained on the sieves enabled the determination of the cumulative percentage passing each sieve.

DESCRIPTION OF LABORATORY TESTING PROGRAM

Sample Preparation

In procuring aggregate for the evaluation program, good to excellent quality material was sought. Poor quality aggregates would breakdown during the sieving operations and lead to erroneous conclusions. The aggregate was obtained from the Armbro-McCormick pit near Caledon, Ontario. The petrographic number for the Granular A material from this source would be about 150.

To determine if the gradation of the material being tested has an effect on the accuracy and reliability of the test results obtained by the different methods, two different gradings of material were prepared. These two gradings were chosen to closely represent the fine and coarse limits of the M.T.C. Granular A specification band (See Figure 2). For each grading, five samples of about 16 kg were required for the testing program devised. To minimize the variation of gradation between the five samples, the collected material was prepared by washing, drying, and separating into various grain sizes by sieving through the nest of standard sieves from 37.5 mm to 75 µm. The material was then recombined to the 16 kg sample by mass proportioning the sieved material according to the required gradation.

The final step in sample preparation was adding about 2% moisture to simulate the field moisture condition.

Test Program

Paramount consideration in designing the test program followed statistical principles thereby enabling us to determine if there is a significant difference in the results obtained by different methods. By using statistical techniques, it was possible to drastically reduce the amount of testing required for the evaluation.

The test program devised is shown on the flow chart in Figure 3.

It is known that the different shaking action of the Rotap and Gilson mechanical shakers will result in slight differences in the

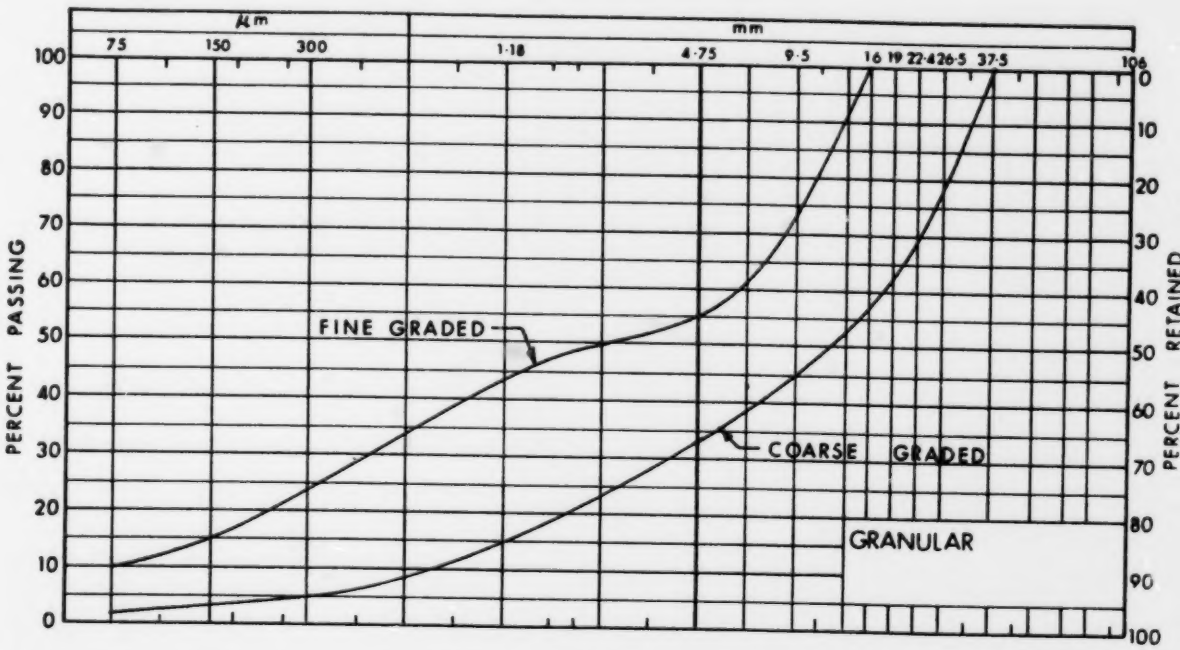

FIGURE 2

ACTUAL GRADATIONS USED FOR THE STUDY

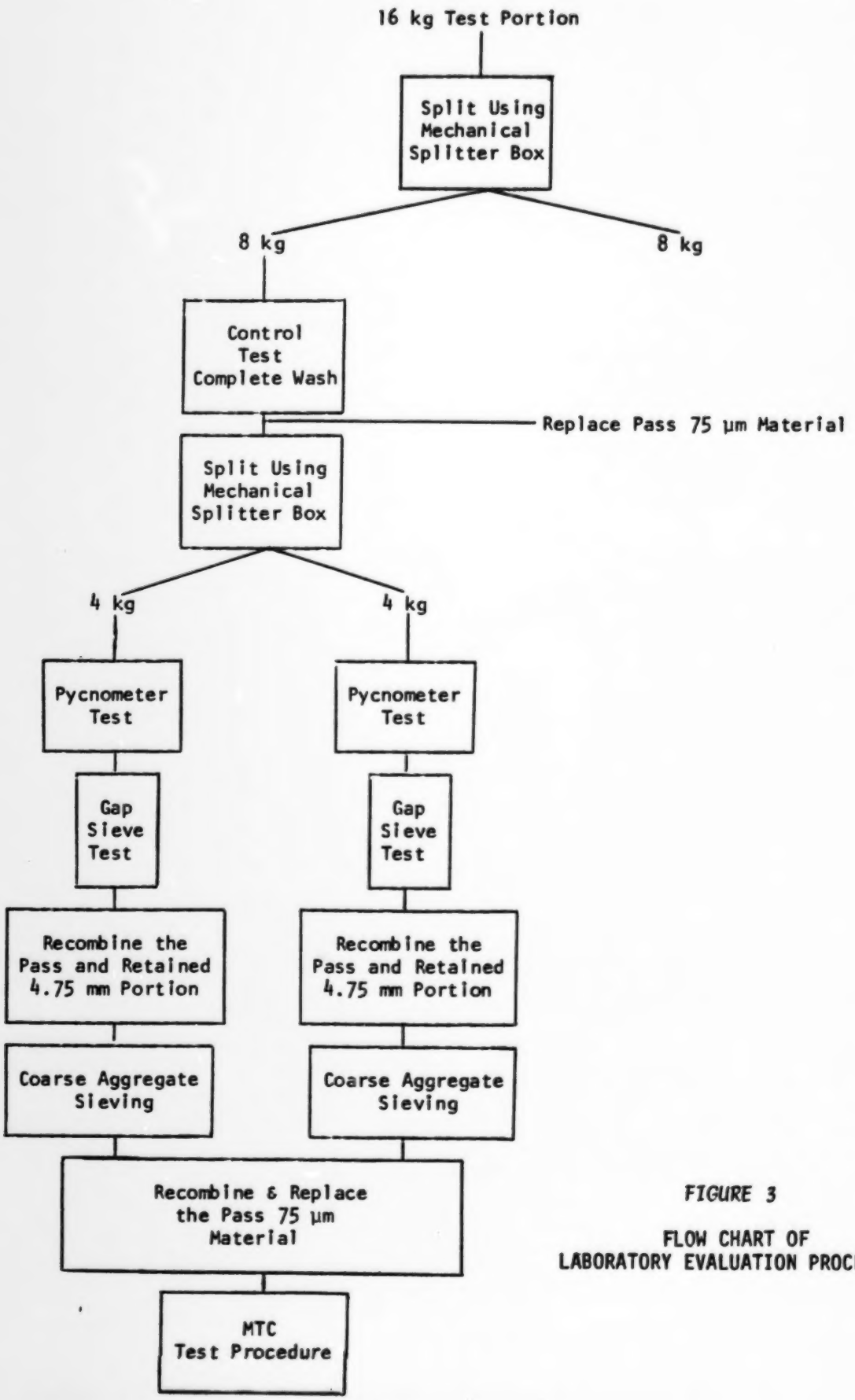

FIGURE 3

FLOW CHART OF
LABORATORY EVALUATION PROCEDURE

gradation test results. The Rotap, with a vertical motion as well as a circular motion in the horizontal plane, produces a slightly more efficient sieving operation than the Gilson shaker which has motion in the horizontal plane only. To reduce this variability in the evaluation program, all sieving was done using Rotap mechanical shakers equipped with 305 mm (12 inch) diameter sieves.

The evaluation program also included the recording of time required for the different tests. The recorded times did not include the time required for splitting, drying or soaking of the aggregate. With regard to the short cut method, this time would amount to about 30 minutes. These methods require that the aggregate be in a saturated surface dry condition which, for most of our aggregates, would necessitate the adding of water and soaking to allow the aggregate to absorb the moisture. According to the M.T.C. procedure, the aggregate is prepared by drying to a constant mass. The time required for drying would depend on the field moisture content of the test portion and the operator's 'opinion' of when further drying would have no effect on the test results. In the Head Office laboratory, this drying time is usually 24 hours. In the construction field laboratories, drying is carried out at higher temperatures for a period of about 30 minutes to 45 minutes. This accelerated drying process is justified on the basis of reduced testing time. Often ignored, however, is the fact that this accelerated drying process may result in altering the material gradation by "popping" of the aggregate. In the evaluation program all drying was carried out using the lower drying temperature, 110^{o}C, and the 24 hour drying period.

The results of the laboratory evaluation program are summarized on Figures 4 and 5.

TEST PROCEDURE	Number of Samples Tested	DESIGNATED SIEVES											
		19.0 mm		9.5 mm		4.75 mm		1.18 mm		300 µm		75 µm	
		% PASSING DESIGNATED SIEVES											
	n	$\bar{X}$	S	$\bar{X}$	S	$\bar{X}$	S	$\bar{X}$	S	$\bar{X}$	S	$\bar{X}$	S
Complete Wash Test	5	100	-	73.94	1.04	56.61	0.90	45.19	0.74	22.50	0.24	8.68	0.68
MTC Test	5	100	-	74.36	0.98	57.56	1.36	46.59	1.26	23.07	0.54	*8.90	0.44
Pycnometer	10											8.56	0.60
Gap Sieving	10					57.17	1.24						
Coarse Aggregate Sieving	10			74.90	1.25	57.40	1.00	46.54	1.40				

* n = 3

FIGURE 4

SUMMARY OF TEST RESULTS ON FINE GRADED MATERIAL

Note: $\bar{X}$ denotes average
S denotes estimate of standard deviation

SUMMARY OF LABORATORY GRADATION

TEST RESULTS FOR SHORT CUT EVALUATION PROGRAM

TEST PROCEDURE	Number of Samples n	DESIGNATED SIEVES													
		37.5 mm		19.0 mm		9.5 mm		4.75 mm		1.18 mm		300 µm		75 µm	
		% PASSING													
		$\bar{X}$	S	$\bar{X}$	S	$\bar{X}$	S	$\bar{X}$	S	$\bar{X}$	S	$\bar{X}$	S	$\bar{X}$	S
Complete Wash	1	100		67.48		47.98		32.98		14.99		5.0		2.51	
MTC	5	100		61.1	2.0	48.7	1.5	34.20	1.1	15.30	0.6	5.3	0.4	2.1	0.3
Pycnometer	10													2.1	0.2
Gap Sieving	10							35.10	2.3						
Coarse Aggregate Sieving	10			69.8	2.5	50.5	2.7	35.80	2.2	16.70	1.8				

FIGURE 5

SUMMARY OF TEST RESULTS ON COARSE GRADED MATERIAL

Note: $\bar{X}$ denotes average
S denotes estimate of standard deviation

EVALUATION OF VARIOUS TEST PROCEDURES

Testing Time

The time recorded for performing each of the different procedures is given below. As previously mentioned, this testing time does not include the sample preparation time. An estimate of this additional time is also given below.

Test Procedure	Average Recorded Testing Time (Minutes)	Estimated Sample Preparation Time (Minutes)	Total Estimated Time Required (Minutes)
M.T.C.	90	30-45	120-135
Pycnometer	30	30	60
Gap Sieving and Pycnometer	35	30	65
Coarse Aggregate Sieving and Pycnometer	50	30	80

As indicated in the above table a combination of the pycnometer and gap sieving procedure would require 65 minutes compared with about 120 minutes for the M.T.C. method. This would approximately double the maximum production rate of the testing facility.

A combination of the pycnometer and coarse aggregate sieving would result in about 40 minutes of time saved per test. Even this would increase production by about 30%.

Evaluation of Test Methods for Accuracy and Precision

The accuracy of any test method is a measure of how close the average value of the test results are to the true mean value. On the other hand, the precision of a test relates to the scatter or variability of the individual test results. Even though the mean value determined may not be equal to the true mean, the procedure may be precise if the individual results are always higher or consistently lower than the true mean.

It should be noted that accuracy and precision are completely different terms. A test method may have good precision if all test results are very close, but the accuracy can be good or poor depending on how close the average result is to the true mean value. Alternatively the precision could be poor, indicating a large scatter of the test results, whereas the accuracy may be either poor or good.

The precision of the test will affect the acceptability of materials with statistical specifications that control the material variability. In our granular material specification, the variability is controlled by a lot range criterion. Test procedures with poor precision will indicate larger material variation or higher lot ranges. Since our specifications are designed to be realistically attainable, it would be necessary to modify the specification to recognize the apparent increase in material variability due to testing by methods with poor precision.

The test accuracy affects material acceptability in that the average test result may be equal to, greater than, or less than the true mean value. If the test precision is good, then we can devise corrections for tests with poor accuracy.

It should now be apparent that test methods giving both poor accuracy and poor precision are undesirable. The best testing procedure would entail both good precision and good accuracy. The foregoing discussion is summarized in the following table.

		TEST PRECISION	
		GOOD	POOR
TEST ACCURACY	POOR	Acceptable Test Method but Apply Correction to Lot Mean Value	Unacceptable Test Method
	GOOD	Acceptable Test Method	Acceptable Test Method but Modify Allowable Range to Accommodate Increase of Apparent Material Variability

In order to evaluate the various test methods with regard to accuracy and precision, the percent passing determined by the different methods was plotted against the percentage passing by the complete wash test. These plots are given on Figures 6, 7 and 8 for the Percentage Passing the 75 µm Sieve, the Percentage Passing the 4.75 mm Sieve, and the Percentage Passing the Coarse Aggregate Sieves (the 9.5 mm, 4.75 mm and 1.18 mm sieves) respectively. Test results plotting on the 45° line shown on the figures means that the applicable test procedure gave the same results as the complete wash test. The farther the test results are from the line, the more inaccurate the particular test.

A cursory inspection of these plots indicates the following:

1. For the pass 75 µm sieve (Figure 6) inspection shows that the M.T.C. procedure gave less scatter, or slightly more precision, than the pycnometer method. However, the M.T.C. method gave slightly higher values of percentage passing than both the pycnometer and the complete wash test.

2. On the 4.75 mm sieve (Figure 7), the Gap Sieving Method showed more precision (less scatter of results) than the M.T.C. method. Both methods gave results slightly higher than the complete wash test.

3. On the coarse aggregate sieves (See Figure 8), both the 9.5 and 4.75 mm sieves, the M.T.C. method and coarse aggregate sieving method showed roughly equal scatter of data and about the same accuracy (which was only slightly higher than the complete wash test). On the 1.18 mm sieve, the results by the coarse aggregate sieving method showed higher scatter than the M.T.C. test procedure.

As a means of gaining further insight into the precision and accuracy of the tests, the data was further analysed using statistical methods of hypothesis testing for both the mean (average value of test results) and variance (measure of dispersion of test results). The analysis method followed is described in a textbook entitled *"Statistics: An Introduction"* by Rickmers and Todd (3). It is not within the scope of this report to describe fully the method of hypothesis testing; however, the interested reader can refer to any basic statistics book including the one previously referred to. The assumptions and results of the analysis are contained in Appendix B for those versed in this subject. Based on the analysis the following conclusions were drawn.

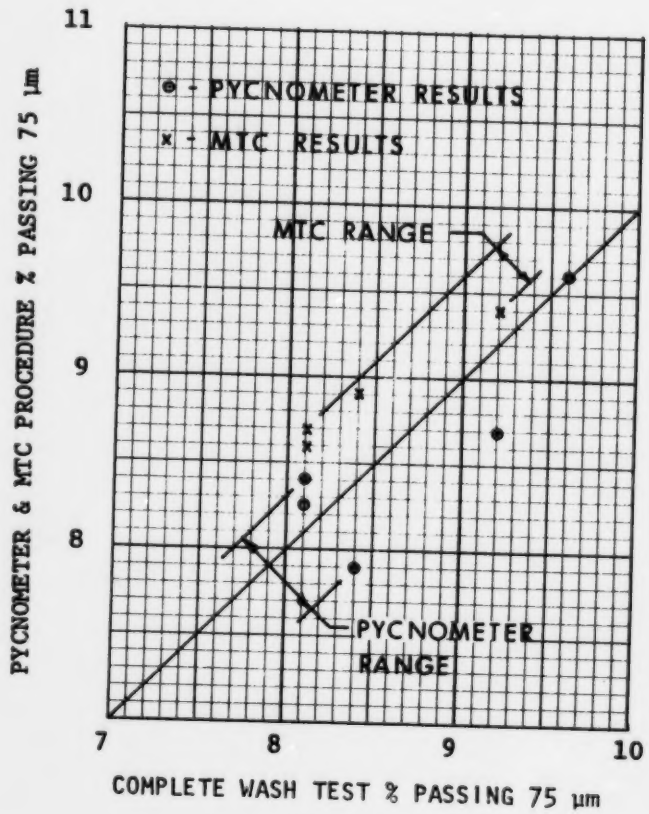

FIGURE 6

PERCENT PASSING 75 µm SIEVE

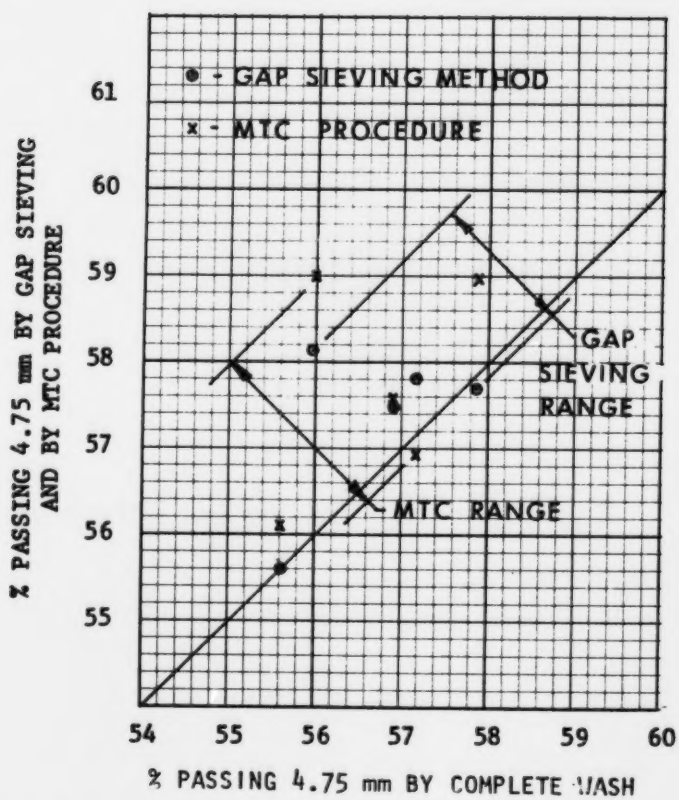

FIGURE 7
PERCENTAGE PASSING 4.75 mm SIEVE

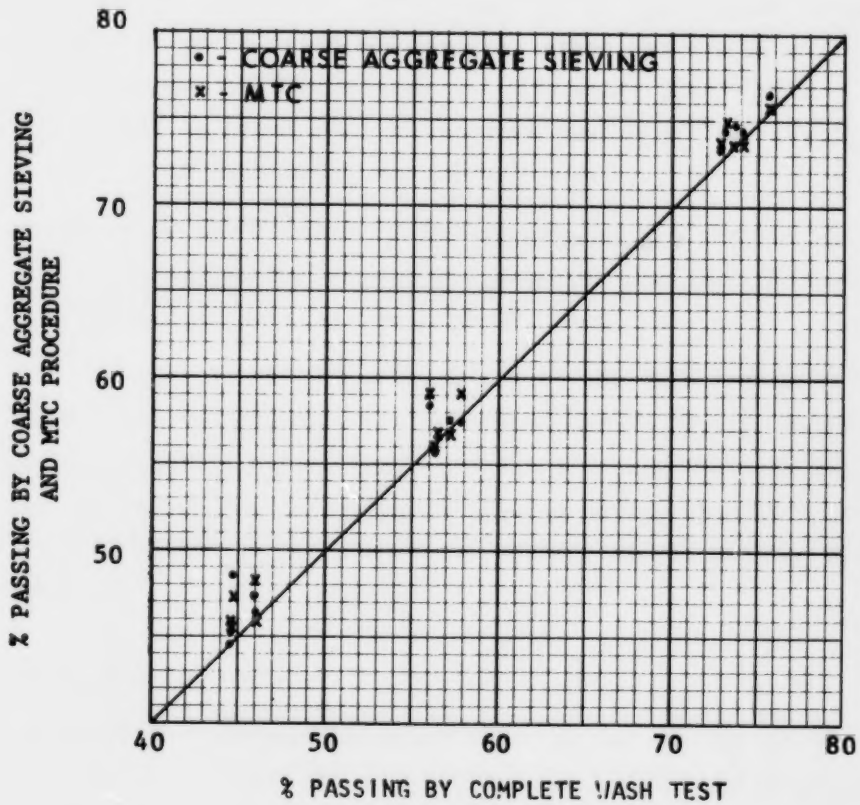

FIGURE 8

PERCENTAGE PASSING COARSE AGGREGATE SIEVES
(9.5 mm, 4.75 mm, 1.18 mm)

1. There is no significant difference between the results obtained by either the M.T.C. method or the Pycnometer Method, and the complete wash test for the percentage passing the 75 µm sieve.
2. There is no significant difference in the results obtained by using either the Gap Sieve Method or the M.T.C. method, and the complete wash test in determining the percentage passing the 4.75 mm sieve.
3. There is no significant difference between the results obtained by using the Coarse Aggregate Sieving Method or the M.T.C. method, and the complete wash test when determining the percentage passing the 9.5 mm and 4.75 mm sieves.
4. There is a significant difference between the results obtained by using the Coarse Aggregate Sieving Method and the complete wash test method when determining the percentage passing the 1.18 mm sieve. (It should be noted that in the Iowa Method of Test sieving on screens smaller than 2.00 mm is not done).
5. There is no significant difference between the results obtained by using the M.T.C. method and the complete wash test when determining the percentage passing the 1.18 mm sieve.

In summary, a thorough examination of the data indicated that both the short cut gradation test methods and the M.T.C. methods are within acceptable accuracy and precision limits. The only exception to this is in the Coarse Aggregate Sieving Method when attempts are made to determine the percentage passing sieves smaller than 4.75 mm.

Equipment Required

A comparison of the equipment required for the different procedures is given in Figure 10. The main difference in the required equipment is the absence of an oven or other drying equipment when using the short cut gradation test procedures. The short cut methods would, however, require more water. About 20 L to 30 L would be sufficient for a combination of the pycnometer and coarse aggregate sieving methods. One additional large plastic container was needed for performing the short cut methods.

FIGURE 10

X DENOTES REQUIRED EQUIPMENT

LIST OF LABORATORY EQUIPMENT	MTC FIELD TEST PROCEDURE	SHORT CUT METHODS		
		GAP SIEVING AND PYCNOMETER METHOD	PYCNOMETER	COARSE AGGREGATE SIEVE AND PYCNOMETER METHOD
Splitter to Reduce Field Sample	X	X	X	X
Scale Up to 25 kg	X			
Scale Up to 1000 g	X			
Scale Up to 10 kg		X	X	X
Sieves 37.5 mm	X			X
26.5 mm	X			X
22.4 mm	X			X
16.0 mm	X			X
13.2 mm	X			X
9.5 mm	X			X
4.75 mm	X	X		X
1.18 mm	X	X	X	X
300 µm	X			
150 µm	X			
75 µm	X	X	X	X
Oven or Stove	X			
Mechanical Shaker	Optional			Optional
Splitter to Reduce Pass 4.75 mm	X			
Pans for Drying	X			
Small Bowls or Pans for Weighing	X	X		X
Rubber Mallet	X			X
12" Diameter 75 µm Sieve	X			
Water	X	X	X	X
Syringe	X	X	X	X
Pycnometer Jar		X	X	X
Thermometer		Optional	Optional	Optional
Funnel				
Large Pan to Accommodate 305 mm Diameter Sieve		X	X	X

The pycnometer jar for determining the pass 75 µm quantity was manufactured by modifying an existing sand cone apparatus. The top cone of the outdated compaction test equipment was removed leaving a hole with a diameter of about 5.0 mm. The glass jar was originally used but was abandoned because of the tendency to break during the test. Stout plastic jars were obtained as a replacement and were found to perform satisfactorily.

Funnels for putting aggregate into the jar, although not used in the study, were suggested by the testing technicians as helpful additional equipment.

Limitations of the Short Cut Methods

The main drawback of these short cut methods is the fact that determination of all the specified sieves is not possible. The pycnometer test determines only the percentage by mass passing the 75 µm sieve. A combination of the Gap Sieving and Pycnometer Method would provide data for the 4.75 mm and 75 µm sieves only. The Coarse Aggregate Sieving and the Pycnometer Method would provide information on all sieves except those between 4.75 mm and 75 µm.

CONCLUSIONS

1. A combination of the Pycnometer Method and the Gap Sieving technique will give the percentage passing the 4.75 mm sieve and the 75 µm sieve in about one half the time required for determining the same results by the M.T.C. method. Furthermore, use of these short cut methods would result in about the same level of accuracy and precision as the existing M.T.C. method.

2. A combination of the Pycnometer Method and Coarse Aggregate Sieving procedure would give the coarse aggregate grading from the maximum particle size down to and including the 4.75 mm sieve in about 70% of the time required to obtain the same data by the M.T.C. procedure. In addition, the accuracy and precision would be the same as the existing method.

3. The Coarse Aggregate Sieving procedure is neither accurate nor precise for sieving particles smaller than 4.75 mm.

RECOMMENDATION

It has been shown that the Short Cut Methods studied have distinct advantages over the current methods used. The main drawback of the methods is that the percentage passing is not obtained for all of the specified sieves. The short cut methods could be applied in the following circumstances:

1. Where testing is performed for information purposes only and a complete gradation is not required.
2. Where acceptance testing does not necessitate information on sieves between 4.75 mm and 75 µm.

ACCORDINGLY, IT IS RECOMMENDED THAT THE THREE SHORT CUT GRADATION TEST METHODS BE INCLUDED IN THE MINISTRY"S LABORATORY TESTING MANUAL.

ACKNOWLEDGEMENTS

The contributions of Mr. Doug Boothe and Mr. Ken Zasitko in procuring the materials, carrying out the evaluation program and assisting in the write up of the test procedures is gratefully acknowledged.

Mr. Howard Reed and Mr. Karan Ganesh were helpful in carrying out some of the statistical analysis for the evaluation.

Mr. Reed's attention to the careful preparation of figures is appreciated.

Miss Joanne Hiron's effort in typing is also gratefully acknowledged.

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APPENDIX A

M.T.C. CONSTRUCTION FIELD TEST PROCEDURE FOR GRAIN SIZE ANALYSIS OF FINE AND COARSE AGGREGATES (REFERENCE M.T.C. LABORATORY TEST LS-602

This test is used to determine the percent of different particle sizes of fine and coarse aggregates by sieving.

Apparatus

- Scale or Balance: accurate within 0.1% of test load, up to 25 kg.
- Scale or Balance: accurate within 0.1% of test load, up to 1000 g.
- Sieves: with square openings and of suitable sizes to furnish the information required for the material type to be tested. Lids and pans required for each series or sets of sieves.
- Oven or stove: of appropriate size capable of maintaining a uniform temperature for drying the sample at a constant mass. Recommended temperature for drying $110^{\circ} \pm 5^{\circ}C$.
- Mechanical Shaker: to accommodate 200 mm diameter sieves for fine aggregate samples.
- Splitter to reduce the pass 4.75 mm material.
- Large pans for drying bulk samples.
- Small bowls or pans for sieved materials for retaining, washing and drying sample portions.
- Rubber mallet: for freeing particles in coarse sieves.
- 300 mm diameter, 75 µm sieve: to wash pass 4.75 mm material.
- Water: for washing fine aggregate samples.

Procedure

- Form PR-D-1 is used for recording and computation of the gradation test.
- The sample is prepared for testing by first reducing the original sample by splitting or quartering to the test sample size as shown in the following table:

MATERIAL	MINIMUM SAMPLE SIZE
Granular 'A'	8 kg
16 mm Crushed 'A' & 'B'	4 kg
*Granular 'B' & 'C'	12 kg
Granular 'D'	2 kg

*Sizes larger than 37.5 mm can be removed from sample and hand sieved through larger specified sieves. Weigh and record the mass removed and add this amount to the mass retained on the next specified sieve.

- The sample is dried to a constant mass.
- Place the sample in the uppermost of a progressive series of coarse sieves selected according to the material requirements or test conditions and vibrate by means of a lateral and vertical motion of the sieve accompanied by a jarring action so as to keep the sample moving continuously over the surface of the sieve. Continue the sieving operation for approximately ten minutes. In no case should the particles be manipulated or turned through the sieve by hand.
- On completion of the coarse sieving operation separate the sieves, weigh and record, cumulatively, the mass of the fraction retained on each sieve.
- Record the cumulative mass retained on the 4.75 mm sieve as the coarse aggregate portion of the sample.
- Weigh and record the pass 4.75 mm material, (pan portion of the coarse aggregate sieve series) for the mass of the fine aggregate portion of the sample.
- Add the coarse and fine aggregate masses to obtain total mass of sample.
- If a percent crushed test is to be performed, retain the coarse aggregate portion of the sample.
- Fine aggregate samples (pass 4.75 mm material) for sieve analysis testing should be reduced in size by splitting to approximately 250 g. If the submitted sample has a very fine grading, it is not only permissible but desirable to reduce the sample size to approximately 125 g to prevent overloading of one or more sieves.
- Weigh and record the mass of fine aggregate before carrying out the washing procedures.

- Place the fine aggregate sample in a container and cover it with sufficient water. Agitate the sample with vigor by shaking and/or stirring with finger to result in complete separation of all particles finer than the 75 µm sieve, being careful to avoid any spillage or decantation of the coarser particles while pouring the wash water over a 75 µm sieve. (Wet the 75 µm sieve mesh before using to allow the wash water to pass through). Repeat this procedure with additional changes of water until the wash water is clear.
- Wash all material retained on the 75 µm sieve and return this material to the container, drain off any excess water and dry sample to a constant mass.
- Weigh and record the washed fine aggregate sample after drying.
- Place the dried sample in the uppermost of a series of fine sieves selected according to the material requirements or test conditions and vibrate for eight minutes using a mechanical shaker.
- On completion of the sieving operation weigh and record, cumulatively, the mass of the fraction retained on each sieve.

Calculations

- Calculate the percent coarse aggregate in the sample as follows:

$$\frac{\text{Coarse Aggregate mass}}{\text{Total sample mass}} \times 100$$

If using Form PR-D-1, $\frac{B}{A} \times 100 = \%$ Coarse Aggregate

- Calculate the percent fine aggregate as follows:

$$\frac{\text{Fine Aggregate mass}}{\text{Total sample mass}} \times 100$$

If using Form PR-D-1, $\frac{C}{A} \times 100 = \%$ Fine Aggregate

- Calculate the cumulative percent passing on each sieve for the coarse aggregate as follows:

$$\frac{\text{mass total sample - mass retained each sieve}}{\text{mass of total sample}} \times 100$$

If using Form PR-D-1, $\frac{A - X}{A} \times 100 = \%$ Passing

- Calculate the cumulative percent passing on each sieve for the fine aggregate as follows:

$$\frac{\left(\begin{array}{c}\text{mass of fine aggregate sample} \\ \text{before washing}\end{array}\right) - \left(\begin{array}{c}\text{mass retained} \\ \text{each sieve}\end{array}\right)}{\text{mass of fine aggregate before washing}} \times \begin{array}{c}\text{percent of} \\ \text{fine aggregate}\end{array}$$

If using Form PR-D-1, $\frac{F - Y}{F} \times E = \%$ Passing

General Notes and Precautions

Check all sieves regularly to ensure that the mesh is free from defects and distortion. Fine mesh sieves, if blinded by sand particles, can be cleaned using an ultrasonic bath. Small holes or breaks in fine mesh sieves may be repaired with an appropriate epoxy.

When emptying each of the fine sieves, invert the sieve into a clean bowl or container, raise sieve approximately five to ten centimeters bring sieve downward with a sharp blow into the bowl to dislodge any particles still remaining in the sieve. Care should be taken during this operation not to push thumbs or fingers into the fine mesh of the sieves. Brushing the bottom of the inverted sieve gently but firmly with the proper sieve brush using a circular motion can also be done on all sieves but the 75 µm. Never use a brush to clean or empty the 75 µm sieve as this may cause distortion of the fine mesh. The above method ensures that all fine particles are included with the sample and that the sieve is kept clean and its efficiency maintained.

It is recommended to insert additional sieves during sieving operations for some gradation specifications to distribute the sample fractions equally over the set of sieves used.

After the sieving operation if it is apparent that one or more of the sieves has been overloaded (blinded) return the sample to a container and reduce to smaller portions, resieve each portion of the sample, summing the results of each portion for final test results.

COMPLETE WASH TEST PROCEDURE

This test method was used as a control test for the basis of evaluating the other procedures.

Apparatus

- Scale or balance: sensitive to 1 g with a 10 kg capacity.
- Sieves: 300 mm diameter sieves conforming to the requirements of ASTM E-11.
- Shaker: mechanical Rotap Sieve Shaker (Gilson Mechanical Shakers may be used for coarse aggregate).
- Oven: forced air electric oven able to maintain a temperature of $110^{o} \pm 5^{o}C$.
- Miscellaneous pans and bowls.

Procedure

- Split sample to an 8 kg test portion size.
- Dry sample to a constant mass and allow to cool to room temperature.
- Weigh on the balance and record the total mass of the dried sample.
- Place the sample in a container and cover with water. Agitate the contents to separate the fines and pour over a 75 µm sieve. Repeat until the wash water is clear.
- Return the material retained on the 75 µm sieve to the container.
- Dry sample to a constant mass and allow to cool to room temperature. Weigh and record the dry mass of the washed sample.
- Sieve the entire sample through a nest of 300 mm diameter sieves on the mechanical shaker for 10 minutes. Sieving on the coarse aggregates sieves (37.5 mm, 22.4 mm, 19 mm, 9.5 mm) is carried out in one increment. Sieving on the 4.75 mm, 1.18 mm, 300 µm and 75 µm is carried out in multiple increments to prevent overloading of the sieves.
- The mass retained on each sieve is then weighed and recorded as the cumulative amount passing.

Calculations

- The percentage passing the various sieves is calculated by dividing the cumulative mass passing each sieve by the total dry mass of the sample.before washing.
- The percentage passing the 75 µm sieve is calculated by subtracting the total dry mass after washing from the total dry mass before washing and dividing the result by the total dry mass before washing.

PYCNOMETER TEST PROCEDURE

This test method provides a rapid test to determine the mass of material finer than 75 µm and is based on the *Kentucky Method of Test for Percentage of Material Finer than a No. 200 (75 µm) sieve by use of a Pycnometer.*

Apparatus

- Scale or balance: sensitive to 1 g with a 10 kg capacity.
- Pycnometer: a 3.8 L plastic "Soil Test" jar fitted with a pycnometer top (See Figure 1).
- Container: large enough to accommodate a 300 mm diameter sieve and prevent the loss of material.
- Syringe.
- Funnel.
- Towel.
- Sieves: a nest of two 300 mm diameter sieves the upper being a 1.18 mm sieve and the lower a 75 µm sieve.

Test Sample Preparation

- The test portion is prepared from the field sample by splitting or quartering in accordance with AASHTO T 248-74.
- The test portion mass should be 4 to 5 kg for aggregates with a nominal maximum sieve size up to and including 37.5 mm.

Procedure

- Place the test portion in the jar and fill with water until the level is well above the aggregate but allow enough space to remain such that the sample may be thoroughly agitated.
- Place the pycnometer top on the jar and roll, invert and agitate the pycnometer to eliminate air bubbles. Care must be taken to avoid the loss of any material.
- Complete filling the pycnometer with water, wipe all excess water from the outside of the pycnometer and determine the total mass of the pycnometer, sample and water to the nearest gram. Record this mass as W_1.

- Remove the pycnometer top and immediately pour the wash water over the nested sieves, taking care to avoid, as much as possible, the decantation of coarse particles of the sample.
- Refill the pycnometer until it is again filled to about 80 to 90 percent capacity and thoroughly agitate the sample to dislodge finer fractions from the coarse particles and bring the fine material into suspension. (Agitation of the sample can be accomplished by leaving the pycnometer top in place, placing a finger over the opening and shaking the sample within the pycnometer, or by leaving the top off and covering the jar opening with the hand, inverting, and shaking the sample. In either case, avoid losing any of the sample). Decant the wash water over the set of nested sieves as above.
- Repeat above procedures until the wash water becomes clear.
- By use of a syringe, wash any material retained on the nested sieves back into the pycnometer.
- Place the pycnometer top on the jar and complete filling the pycnometer with water, wipe all excess water from outside the pycnometer and determine the total mass as W_2.
- Empty sample from pycnometer and completely fill it with water alone. Wipe off excess water and weigh to the nearest gram. Record this mass as W_{BW}.

  (Note: A chart may be prepared for a particular pycnometer assembly which will provide W_{BW} at various water temperatures. By taking the temperature of the water at the time of test and determining W_{BW} from the chart at the same temperature, it will become unnecessary to weigh the jar full of water for each test. See the sample chart Figure A-1).

Calculation

The results are calculated using the following formula:

$$\text{Percentage of material pass the 75 } \mu\text{m sieve} = \frac{(W_1 - W_2) \times 100}{W_1 - W_{BW}}$$

Where W_1 = Mass of pycnometer filled with water and test portion prior to washing.

W_2 = Mass of pycnometer filled with water and test portion after washing.

W_{BW} = Mass of the pycnometer filled with water alone and at the same temperature as the water used in determining W_1 and W_2.

Comments

The above formula is valid only if the sample under test is either in the saturated surface dry (SSD) condition or contains free moisture as any absorption of water which might take place within the sample during the interim between determination of W_1 and W_2 would introduce errors depending on the original dryness of the sample and its rate of absorption. For this reason aggregates which are drier than the SSD condition at the time they are received for testing or at the time they are removed from stockpiles must be dampened and allowed to absorb water for at least 30 minutes before determination of W_1.

GAP SIEVING (ONE SIEVE METHOD) AND PYCNOMETER TEST PROCEDURE

This method of test covers a procedure for determination of the percent by mass passing the 4.75 mm sieve plus the total percent by mass passing the 75 µm sieve.

Apparatus

The apparatus shall consist of the following:

- Balance: the balance or scale shall be sensitive to within 1 g with a capacity of 10 kg.
- Sieves: 300 mm diameter sieves with square or round openings conforming to ASTM E11.
- Thermometer: with a range to cover the temperature of the water being used during testing.
- Pycnometer: a fruit jar with a nominal capacity of 3.8 L fitted with a pycnometer top.
- Container: large enough to prevent loss of water and material.

Test Sample Preparation

The test portion is prepared by splitting or quartering to a 4 to 5 kg mass for aggregates with a maximum nominal size of up to 37.5 mm.

Procedure

- Add sufficient water to bring the test sample to a saturated surface dry condition and let it stand for 30 minutes.
- Weigh the test sample in air and record the mass as the Original Saturated Surface Dry or Wetter Mass.
- Place the damp test portion in the jar and fill with water until the water level is well above the level of the aggregate, but allow enough space to remain such that the sample may be thoroughly agitated.
- Place the pycnometer top on the jar and roll, invert, and agitate the pycnometer to eliminate air bubbles. Care shall be taken to avoid any loss of material from the pycnometer.

- Complete filling the pycnometer with water, wipe all excess water from outside of pycnometer, and determine the total mass of pycnometer, sample and water to nearest gram. Record this weight as W_1.
- Remove the pycnometer top and immediately pour the wash water over a nest of sieves (a 1.18 mm upper sieve and a 75 µm lower sieve) taking care to avoid, as much as possible, the decantation of coarse particles of the sample.
- Refill the pycnometer until it is again filled to about 80 to 90 percent capacity and thoroughly agitate the sample to dislodge finer fractions from the coarse particles and bring the fine material into suspension. (Agitation of the sample can be accomplished by leaving the pycnometer top in place, placing a finger over the opening and shaking the sample within the pycnometer, or by leaving the top off the sample. In either case, avoid losing any of the sample). Decant the wash water over the set of nested sieves as above.
- Repeat above procedure until the wash water becomes clear.
- By use of a syringe, wash any material retained on the nested sieves back into the pycnometer.
- Place the pycnometer top on the jar and complete filling the pycnometer with water, wipe all excess water from outside the pycnometer and determine the total mass of pycnometer, sample and water. Record this mass as W_2.
- Empty sample from pycnometer onto the critical sieve, 4.75 mm, and wash thoroughly by agitating the sieve and contents vigorously in a container of water.
- Drain as much free water as possible from the washed material.
- Continue sieving until not more than 0.5 percent by mass of the residue passes the sieve in one minute of hand sieving.
- Determine the mass retained on the 4.75 mm sieve by weighing.
- Completely fill pycnometer with water alone. Wipe off excess water and weigh to the nearest gram. Record this mass as W_{BW}.
  (Note: A chart may be prepared for a particular pycnometer assembly which will provide W_{BW}, at various water temperatures. By taking temperature of the water at the time of test and determining W_{BW} from the chart at the same temperature, it will become unnecessary to weigh the pycnometer with water for each test).

Calculations

Percentage passing 75 µm material =

$$\frac{(W_1 - W_2)}{W_1 - W_{BW}} \times 100$$

Where W_1 = Mass of pycnometer filled with water and test portion prior to washing.

W_2 = Mass of pycnometer filled with water and test portion after washing.

W_{BW} = Mass of the pycnometer filled with water alone and at the same temperature as the water used in determining W_1 and W_2.

- To calculate the percentage passing the 4.75 mm sieve, proceed as follows:

Percentage passing the 4.75 mm sieve =

$$\frac{\text{Original Saturated Surface Dry Mass - Mass Retained on the 4.75 mm Sieve}}{\text{Original Saturated Surface Dry Mass}}$$

COARSE AGGREGATE SIEVING AND PYCNOMETER TEST METHODS

This method of test covers a procedure for determining the percentage passing the coarse aggregate sieves and also the percentage passing the 75 µm sieve and is based on the *Iowa Method of Test for Sieve Analysis of Coarse Aggregate (Quick Method)* and the *Kentucky Method of Test for Percentage of Material Finer than a 75 µm (No. 200) Sieve by Use of a Pycnometer.*

Apparatus

The apparatus shall consist of the following:

- Balance: the balance or scale shall be sensitive to 1 g with a capacity of 10 kg.
- Sieves: 300 mm diameter sieves with square or round opening conforming to ASTM E11.
- Pycnometer: a fruit jar with a nominal capacity of 3.8 L fitted with a pycnometer top.
- Thermometer: with a range to cover the temperature of the water being used during testing.
- Container: large enough to prevent loss of water and material.

Test Sample Preparation

The test portion is prepared by splitting or quartering to a 4 to 5 kg mass for aggregates with a maximum nominal size of up to 37.5 mm.

Procedure

- Add sufficient water to bring the test sample to a saturated surface dry condition and let it stand for 30 minutes.
- Weigh the test sample in air and record the mass as the Original Saturated Surface Dry or Wetter Mass.
- Place the saturated surface dry test portion in the jar and fill with water until the water level is well above the level of the aggregate, but allow enough space to remain such that the sample may be thoroughly agitated.

The jar will ordinarily be filled to about 80 to 90 percent of its capacity when using a 5 kg sample.

- Place the pycnometer top on the jar and roll, invert, and agitate the pycnometer to eliminate air bubbles. Care shall be taken to avoid any loss of material from the pycnometer.
- Complete filling the pycnometer with water, wipe all excess water from outside of pycnometer, and determine the total mass of pycnometer, sample and water to the nearest gram. Record this mass as W_1.
- Remove the pycnometer top and immediately pour the wash water over a nest of two sieves, the upper a 1.18 mm and the lower a 75 µm sieve, being careful to avoid the loss of particles.
  Refill the pycnometer until it is again filled to about 80 to 90 percent capacity and thoroughly agitate the sample to dislodge finer fractions from the coarse particles and bring the fine material into suspension. (Agitation of the sample can be accomplished by leaving the pycnometer top in place, placing a finger over the opening and shaking the sample within the pycnometer or by leaving the top off and covering the jar opening with the hand and inverting and shaking the sample. In either case, avoid losing any of the sample). Decant the wash water over the set of nested sieves as above.
- Repeat above procedure until the wash water becomes clear.
- By use of a syringe, wash any material retained on the nested sieves back into the pycnometer.
- Place the pycnometer top on the jar and complete filling the pycnometer with water, wipe all excess water from outside the pycnometer and determine the total mass of pycnometer, sample and water as above. Record this mass as W_2.
- Empty sample from pycnometer on to a 4.75 mm sieve and wash thoroughly by agitating the sieve and contents vigorously in a container of water.
- Drain as much free water as possible from the washed material.
- Sieve the material through the appropriate sieves down to and including the 4.75 mm sieve.
- Weigh the material retained on each sieve and determine the percentage of material passing each sieve.
- Take the empty pycnometer and completely fill it with water. Wipe off excess water and weigh to the nearest gram. Record this mass as W_{BW}.

(Note: A chart may be prepared for a particular pycnometer assembly which will provide W_{BW} at various water temperatures).

Calculations

- To calculate the percentage by mass passing the 75 µm sieve, proceed as follows:

Percentage passing 75 µm material =

$$\frac{(W_1 - W_2)}{W_1 - W_{BW}} \times 100$$

Where W_1 = Mass of pycnometer filled with water and test portion prior to washing.

W_2 = Mass of pycnometer filled with water and test portion after washing.

W_{BW} = Mass of the pycnometer filled with water alone and at the same temperature as the water used in determining W_1 and W_2.

- To calculate the percentage by mass passing the coarse aggregate sieve employ the following formula:

$$\frac{\text{Original Saturated Surface Dry Mass} - \text{Cumulative Mass Retained on Applicable Sieve}}{\text{Original Saturated Surface Dry Mass}} \times 100\%$$

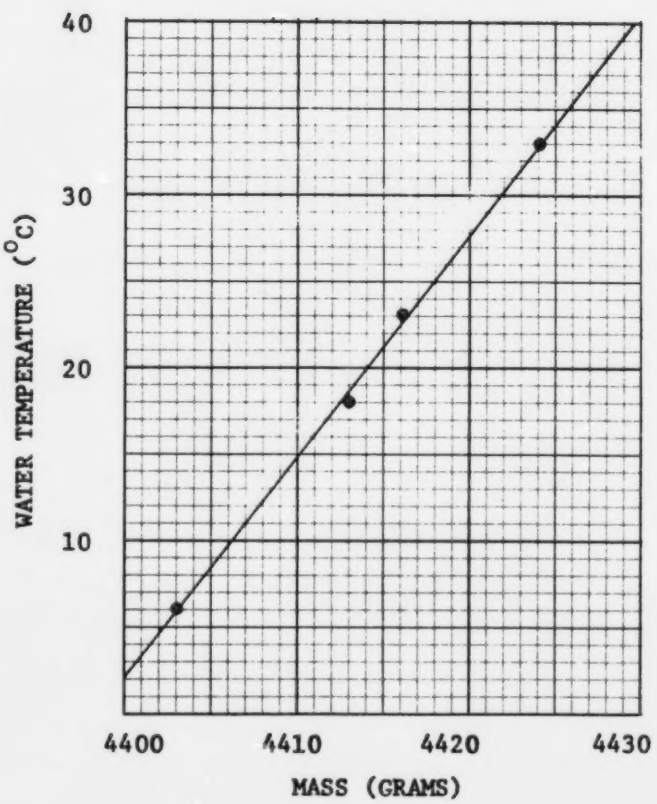


FIGURE A-1

EFFECT OF WATER TEMPERATURE
ON MASS OF PYCNOMETER

APPENDIX B

STATISTICAL EVALUATION OF THE ACCURACY OF THE TEST METHODS

The accuracy of the test methods in comparison to the control test can be evaluated by employing a statistical technique known as hypothesis testing of the means. This technique determines if there is a significant difference in the mean result of two sets of data. If a significant difference is found, then the inferred conclusion is that accuracy of the test procedure in question is not the same as the control test.

The hypothesis test of the means begins by assuming that the two means are from the same population. This assumption is known as the null hypothesis. In order to test this hypothesis, the test statistic is computed by expressing the difference in the means of the two populations in units of the standard error of the mean. The test statistic, t, is then compared with a critical t value obtained from statistical tables. If the test statistic is more than the critical t value, then the null hypothesis is rejected, and the alternate hypothesis is accepted. If the test statistic is less than the critical t value, the conclusion is that there is insufficient evidence to reject the null hypothesis and it is accordingly accepted.

For the analysis of the gradation test results, the null hypothesis is that there is no significant difference between the mean test result by the control test, $\overline{X}_1$, and the mean test result by the test method under consideration, $\overline{X}_2$. Expressed as a formula: $\overline{X}_1 = \overline{X}_2$. The alternate hypothesis is that there is significant difference (i.e. $\overline{X}_1 \neq \overline{X}_2$).

In our case, where there are two populations of size n_1 and n_2 with variances of s_1^2 and s_2^2, the test statistic is calculated as:

$$t = \frac{\overline{X}_1 - \overline{X}_2}{(s_1^2/n_1 + s_2^2/n_2)^{\frac{1}{2}}}$$

Where $\overline{X}_1$ is the mean test result for the control test.

$\overline{X}_2$ is the mean test result for the other test procedure under consideration.

s_1 is an estimate of the standard deviation of test results for the control test.

s_2 is an estimate of the standard deviation of test results for the other test procedure under consideration.

n_1 is the sample size for the control test (number of test results used to complete $\overline{X}_1$ and s_1).

n_2 is the sample size for the other test procedure under consideration.

The applicable degrees of freedom, ν (symbol pronounced NU) is given by:

$$\nu = \frac{(s_1^2/n_1 + s_2^2/n_2)^2}{(s_1^2/n_1)^2/\nu_1 + (s_2^2/n_2)^2/\nu_2}$$

Where s_1, s_2, n_1, n_2 are as described above.

ν_1 is the degrees of freedom associated with the control test ($\nu_1 = n_1 - 1$).

ν_2 is the degrees of freedom associated with the other test procedure under consideration ($\nu_2 = n_2 - 1$).

The critical t value was obtained in the tables of Critical Values of Students t Distribution for the applicable α risk (Type I error associated with rejecting the null hypothesis when it should have been accepted) and degrees of freedom, ν, as calculated by the above formula. The appropriate statistical tables can be found in most texts on statistics. For the information of the reader, an extract of the tables from *Statistics: An Introduction* (3) is included as Figure B-1. It should be noted that the formulation of the null and alternate hypothesis indicates a two tailed test (See Figure B-1).

The t values were compared by dividing the actual t value by the critical t value. The results of these calculations are given on Figure B-2 for results on the fine graded material and on Figure B-3 for the test results on the coarse graded material. Note that the control test for the fine graded material testing was the complete wash test, whereas the control test for the coarse graded material was the M.T.C. procedure.

If the ratio of t actual to t critical is greater than 1, the null hypothesis is to be rejected. Examination of Figures B-2 and B-3 indicates that the ratio is greater than unity for the Coarse Aggregate Sieving Method on the 1.18 mm sieve only. Hence, for the Coarse Aggregate Sieving Test Method the results on the 1.18 mm sieve are not as accurate as are the results by the complete wash test on the 1.18 mm sieve.

A ratio of t actual to t critical less than unity indicates the accuracy of the test under consideration is the same as the accuracy of the control test. Examination of Figures B-2 and B-3 indicates that this is the case for all test methods with the exception as mentioned above.

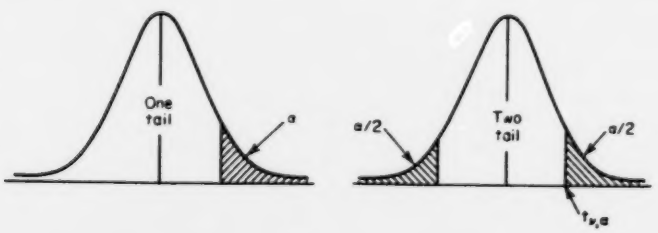
FIGURE B-1

(EXTRACT FROM *Statistics: An Introduction*
RICKMERS & TODD; McGRAW-HILL; 1967)

Critical Values of Student's t Distribution

ν \ α	Two-tail Critical Values						
	0.50	0.25	0.10	0.05	0.025	0.01	0.005
1	1.00000	2.4142	6.3138	12.706	25.452	63.657	127.32
2	0.81650	1.6036	2.9200	4.3027	6.2053	9.9248	14.089
3	0.76489	1.4226	2.3534	3.1825	4.1765	5.8409	7.4533
4	0.74070	1.3444	2.1318	2.7764	3.4954	4.6041	5.5976
5	0.72669	1.3009	2.0150	2.5706	3.1634	4.0321	4.7733
6	0.71756	1.2733	1.9432	2.4469	2.9687	3.7074	4.3168
7	0.71114	1.2543	1.8946	2.3646	2.8412	3.4995	4.0293
8	0.70639	1.2403	1.8595	2.3060	2.7515	3.3554	3.8325
9	0.70272	1.2297	1.8331	2.2622	2.6850	3.2498	3.6897
10	0.69981	1.2213	1.8125	2.2281	2.6338	3.1693	3.5814
11	0.69745	1.2145	1.7959	2.2010	2.5931	3.1058	3.4966
12	0.69548	1.2089	1.7823	2.1788	2.5600	3.0545	3.4284
13	0.69384	1.2041	1.7709	2.1604	2.5326	3.0123	3.3725
14	0.69242	1.2001	1.7613	2.1448	2.5096	2.9768	3.3257
15	0.69120	1.1967	1.7530	2.1315	2.4899	2.9467	3.2860
16	0.69013	1.1937	1.7459	2.1199	2.4729	2.9208	3.2520
17	0.68919	1.1910	1.7396	2.1098	2.4581	2.8982	3.2225
18	0.68837	1.1887	1.7341	2.1009	2.4450	2.8784	3.1966
19	0.68763	1.1866	1.7291	2.0930	2.4334	2.8609	3.1737
20	0.68696	1.1848	1.7247	2.0860	2.4231	2.8453	3.1534
21	0.68635	1.1831	1.7207	2.0796	2.4138	2.8314	3.1352
22	0.68580	1.1816	1.7171	2.0739	2.4055	2.8188	3.1188
23	0.68531	1.1802	1.7139	2.0687	2.3979	2.8073	3.1040
24	0.68485	1.1789	1.7109	2.0639	2.3910	2.7969	3.0905
25	0.68443	1.1777	1.7081	2.0595	2.3846	2.7874	3.0782
26	0.68405	1.1766	1.7056	2.0555	2.3788	2.7787	3.0669
27	0.68370	1.1757	1.7033	2.0518	2.3734	2.7707	3.0565
28	0.68335	1.1748	1.7011	2.0484	2.3685	2.7633	3.0469
29	0.68304	1.1739	1.6991	2.0452	2.3638	2.7564	3.0380
30	0.68276	1.1731	1.6973	2.0423	2.3596	2.7500	3.0298
40	0.68066	1.1673	1.6839	2.0211	2.3289	2.7045	2.9712
60	0.67862	1.1616	1.6707	2.0003	2.2991	2.6603	2.9146
120	0.67656	1.1559	1.6577	1.9799	2.2699	2.6174	2.8599
∞	0.67449	1.1503	1.6449	1.9600	2.2414	2.5758	2.8070
ν \ α	0.25	0.125	0.05	0.025	0.0125	0.005	0.0025
	One-tail Critical Values						

SOURCE: E. S. Pearson, Critical Values of Student's *t* Distribution, *Biometrika*, vol. 32 pp. 168–181, 1941.



TEST PROCEDURE	DESIGNATED SIEVES					
	19.0 mm	9.5 mm	4.75 mm	1.18 mm	300 µm	75 µm
M.T.C.	-	0.29	0.55	0.87	0.88	0.22
Pycnometer						0.13
Gap Sieving			0.45			
Coarse Aggregate Sieving		0.70	0.68	1.12		

FIGURE B-2

RATIOS OF T ACTUAL/T CRITICAL FOR COMPARISON BETWEEN
COMPLETE WASH TEST AND OTHER PROCEDURES FOR THE FINE GRADED MATERIAL

TEST PROCEDURE	DESIGNATED SIEVES						
	37.5 mm	19 mm	9.5 mm	4.75 mm	1.18 mm	300 µm	75 µm
Pycnometer							0
Gap Sieving				0.47			
Coarse Aggregate Sieving		0.63	0.76	0.86	1.02		

FIGURE B-3

RATIOS OF T ACTUAL/T CRITICAL FOR COMPARISON BETWEEN
THE M.T.C. PROCEDURE AND OTHER SHORT CUT METHODS
FOR COARSE GRADED MATERIAL

STATISTICAL EVALUATION OF THE PRECISION OF THE TEST METHODS

It should be noted that precision and variance are both measures of the scatter of individual test results. To gain insight into the precision, we examined the variances of the different test procedures in comparison to the control test. A statistical method known as hypothesis test of variances was employed to determine if the variance, or scatter of data, was significantly different for the various test methods in comparison to the control test.

For this statistical method, the null hypothesis is that there is no significant difference between the variance established by the control test and that established by the other test methods. In mathematical symbols: $\sigma_1^2 = \sigma_2^2$. The alternate hypothesis is that there is a significant difference in the variances (i.e. $\sigma_1^2 \neq \sigma_2^2$).

To test the null hypothesis of variances, the test statistic is computed by dividing the larger of the two variances by the smaller variance. The ratio obtained, known as F actual, is compared with a critical F ratio to determine whether the null hypothesis is rejected or accepted. It should be noted that the F distribution is a non symmetrical distribution, centred about a mean of 1, with positive values only. This distribution describes the frequency histogram of the ratio of two variances estimated by selecting two samples of size n_1 and n_2 from a single population. If F actual is greater than F critical, the null hypothesis is rejected. Alternatively if the F actual is less than F critical, the conclusion reached is that the evidence indicates the null hypothesis cannot be rejected.

The formula used for calculating F actual is:

$$F = \frac{s_1^2 \sigma_2^2}{s_2^2 \sigma_2^2}$$

Since our null hypothesis is $\sigma_1^2 = \sigma_2^2$, the formula becomes:

$$F = \frac{s_1^2}{s_2^2}$$

Where s_1^2 is the largest variance of the control test or the alternate test method under consideration.

s_2^2 is the smallest variance of the control test or the alternate test method under consideration.

ν_1 is the degree of freedom associated with s_1^2 ($\nu_1 = n_1 - 1$).

ν_2 is the degree of freedom associated with s_2^2 ($\nu_2 = n_2 - 1$).

To determine F critical, it is necessary to consult the statistical tables for the Critical Values of the F Distribution. These tables can be found in most statistics books and an extract from *Statistics: An Introduction* (3) is included as Figure B-4. It should be noted that the F critical is a function of ν_1, ν_2 and the α risk. The α risk was assumed to be 0.10; however, since our original hypothesis has formulated a two tailed test, the appropriate α tables are ($\alpha/2 = 0.10/2$) 0.05. (Note: Since this function is not symmetrical, the F value for say $\nu_1 = 5$ and $\nu_2 = 10$ is not the same as the F value for $\nu_1 = 10$ and $\nu_2 = 5$).

For simplicity the ratio of F actual divided by F critical was calculated and is shown on Figure B-5 for the test results on fine graded material and Figure B-6 for the testing done on the coarse graded material. If this ratio is greater than unity, the null hypothesis is rejected, meaning there is a significant difference between the variance obtained by different methods. If the ratio is less than 1.0, there is not sufficient evidence to reject the null hypothesis.

As shown in the figures, the only F actual/F critical ratio greater than unity occurs for the Coarse Aggregate Sieving Method on the 1.18 mm sieve. The conclusion is, therefore, that the precision of all test methods is the same as the control test except for the test result on the 1.18 mm sieve when using the Coarse Aggregate Sieving Method.

Critical Values of the F Distribution

$\alpha = 0.05$

ν_2 \ ν_1	1	2	3	4	5	6	7	8	9	10	12	15	20	24	30	40	60	120	∞
1	161.45	199.50	215.71	224.58	230.16	233.99	236.77	238.88	240.54	241.88	243.91	245.95	248.01	249.05	250.09	251.14	252.20	253.25	254.32
2	18.513	19.000	19.164	19.247	19.296	19.330	19.353	19.371	19.385	19.396	19.413	19.429	19.446	19.454	19.462	19.471	19.479	19.487	19.496
3	10.128	9.5521	9.2766	9.1172	9.0135	8.9406	8.8868	8.8452	8.8123	8.7855	8.7446	8.7029	8.6602	8.6385	8.6166	8.5944	8.5720	8.5494	8.5265
4	7.7086	6.9443	6.5914	6.3883	6.2560	6.1631	6.0942	6.0410	5.9988	5.9644	5.9117	5.8578	5.8025	5.7744	5.7459	5.7170	5.6878	5.6581	5.6281
5	6.6079	5.7861	5.4095	5.1922	5.0503	4.9503	4.8759	4.8183	4.7725	4.7351	4.6777	4.6188	4.5581	4.5272	4.4957	4.4638	4.4314	4.3984	4.3650
6	5.9874	5.1433	4.7571	4.5337	4.3874	4.2839	4.2066	4.1468	4.0990	4.0600	3.9999	3.9381	3.8742	3.8415	3.8082	3.7743	3.7398	3.7047	3.6688
7	5.5914	4.7374	4.3468	4.1203	3.9715	3.8660	3.7870	3.7257	3.6767	3.6365	3.5747	3.5108	3.4445	3.4105	3.3758	3.3404	3.3043	3.2674	3.2298
8	5.3177	4.4590	4.0662	3.8378	3.6875	3.5806	3.5005	3.4381	3.3881	3.3472	3.2840	3.2184	3.1503	3.1152	3.0794	3.0428	3.0053	2.9669	2.9276
9	5.1174	4.2565	3.8626	3.6331	3.4817	3.3738	3.2927	3.2296	3.1789	3.1373	3.0729	3.0061	2.9365	2.9005	2.8637	2.8259	2.7872	2.7475	2.7067
10	4.9646	4.1028	3.7083	3.4780	3.3258	3.2172	3.1355	3.0717	3.0204	2.9782	2.9130	2.8450	2.7740	2.7372	2.6996	2.6609	2.6211	2.5801	2.5379
11	4.8443	3.9823	3.5874	3.3567	3.2039	3.0946	3.0123	2.9480	2.8962	2.8536	2.7876	2.7186	2.6464	2.6090	2.5705	2.5309	2.4901	2.4480	2.4045
12	4.7472	3.8853	3.4903	3.2592	3.1059	2.9961	2.9134	2.8486	2.7964	2.7534	2.6866	2.6169	2.5436	2.5055	2.4663	2.4259	2.3842	2.3410	2.2962
13	4.6672	3.8056	3.4105	3.1791	3.0254	2.9153	2.8321	2.7669	2.7144	2.6710	2.6037	2.5331	2.4589	2.4202	2.3803	2.3392	2.2966	2.2524	2.2064
14	4.6001	3.7389	3.3439	3.1122	2.9582	2.8477	2.7642	2.6987	2.6458	2.6021	2.5342	2.4630	2.3879	2.3487	2.3082	2.2664	2.2230	2.1778	2.1307
15	4.5431	3.6823	3.2874	3.0556	2.9013	2.7905	2.7066	2.6408	2.5876	2.5437	2.4753	2.4035	2.3275	2.2878	2.2468	2.2043	2.1601	2.1141	2.0658
16	4.4940	3.6337	3.2389	3.0069	2.8524	2.7413	2.6572	2.5911	2.5377	2.4935	2.4247	2.3522	2.2756	2.2354	2.1938	2.1507	2.1058	2.0589	2.0096
17	4.4513	3.5915	3.1968	2.9647	2.8100	2.6987	2.6143	2.5480	2.4943	2.4499	2.3807	2.3077	2.2304	2.1898	2.1477	2.1040	2.0584	2.0107	1.9604
18	4.4139	3.5546	3.1599	2.9277	2.7729	2.6613	2.5767	2.5102	2.4563	2.4117	2.3421	2.2686	2.1906	2.1497	2.1071	2.0629	2.0166	1.9681	1.9168
19	4.3808	3.5219	3.1274	2.8951	2.7401	2.6283	2.5435	2.4768	2.4227	2.3779	2.3080	2.2341	2.1555	2.1141	2.0712	2.0264	1.9796	1.9302	1.8780
20	4.3513	3.4928	3.0984	2.8661	2.7109	2.5990	2.5140	2.4471	2.3928	2.3479	2.2776	2.2033	2.1242	2.0825	2.0391	1.9938	1.9464	1.8963	1.8432
21	4.3248	3.4668	3.0725	2.8401	2.6848	2.5727	2.4876	2.4205	2.3661	2.3210	2.2504	2.1757	2.0960	2.0540	2.0102	1.9645	1.9165	1.8657	1.8117
22	4.3009	3.4434	3.0491	2.8167	2.6613	2.5491	2.4638	2.3965	2.3419	2.2967	2.2258	2.1508	2.0707	2.0283	1.9842	1.9380	1.8895	1.8380	1.7831
23	4.2793	3.4221	3.0280	2.7955	2.6400	2.5277	2.4422	2.3748	2.3201	2.2747	2.2036	2.1282	2.0476	2.0050	1.9605	1.9139	1.8649	1.8128	1.7570
24	4.2597	3.4028	3.0088	2.7763	2.6207	2.5082	2.4226	2.3551	2.3002	2.2547	2.1834	2.1077	2.0267	1.9838	1.9390	1.8920	1.8424	1.7897	1.7331
25	4.2417	3.3852	2.9912	2.7587	2.6030	2.4904	2.4047	2.3371	2.2821	2.2365	2.1649	2.0889	2.0075	1.9643	1.9192	1.8718	1.8217	1.7684	1.7110
26	4.2252	3.3690	2.9751	2.7426	2.5868	2.4741	2.3883	2.3205	2.2655	2.2197	2.1479	2.0716	1.9898	1.9464	1.9010	1.8533	1.8027	1.7488	1.6906
27	4.2100	3.3541	2.9604	2.7278	2.5719	2.4591	2.3732	2.3053	2.2501	2.2043	2.1323	2.0558	1.9736	1.9299	1.8842	1.8361	1.7851	1.7307	1.6717
28	4.1960	3.3404	2.9467	2.7141	2.5581	2.4453	2.3593	2.2913	2.2360	2.1900	2.1179	2.0411	1.9586	1.9147	1.8687	1.8203	1.7689	1.7138	1.6541
29	4.1830	3.3277	2.9340	2.7014	2.5454	2.4324	2.3463	2.2782	2.2229	2.1768	2.1045	2.0275	1.9446	1.9005	1.8543	1.8055	1.7537	1.6981	1.6377
30	4.1709	3.3158	2.9223	2.6896	2.5336	2.4205	2.3343	2.2662	2.2107	2.1646	2.0921	2.0148	1.9317	1.8874	1.8409	1.7918	1.7396	1.6835	1.6223
40	4.0848	3.2317	2.8387	2.6060	2.4495	2.3359	2.2490	2.1802	2.1240	2.0772	2.0035	1.9245	1.8389	1.7929	1.7444	1.6928	1.6373	1.5766	1.5089
60	4.0012	3.1504	2.7581	2.5252	2.3683	2.2540	2.1665	2.0970	2.0401	1.9926	1.9174	1.8364	1.7480	1.7001	1.6491	1.5943	1.5343	1.4673	1.3893
120	3.9201	3.0718	2.6802	2.4472	2.2900	2.1750	2.0867	2.0164	1.9588	1.9105	1.8337	1.7505	1.6587	1.6084	1.5543	1.4952	1.4290	1.3519	1.2539
∞	3.8415	2.9957	2.6049	2.3719	2.2141	2.0986	2.0096	1.9384	1.8799	1.8307	1.7522	1.6664	1.5705	1.5173	1.4591	1.3940	1.3180	1.2214	1.0000

FIGURE B-4

(EXTRACT FROM *Statistics: An Introduction)*

RICKMERS & TODD; McGRAW-HILL, 1967)

TEST PROCEDURE	DESIGNATED SIEVES					
	19.0 mm	9.5 mm	4.75 mm	1.18 mm	300 µm	75 µm
M.T.C.		0.18	0.36	0.45	0.79	0.37
Pycnometer						0.35
Gap Sieving			0.32			
Coarse Aggregate Sieving		0.24	0.20	0.60		

FIGURE B-5

RATIOS OF F ACTUAL/F CRITICAL FOR
VARIOUS TEST PROCEDURES COMPARED WITH
CONTROL TEST FOR FINE GRADED MATERIAL

TEST PROCEDURE	DESIGNATED SIEVES						
	37.5 mm	19 mm	9.5 mm	4.75 mm	1.18 mm	300 µm	75 µm
Pycnometer							0.38
Gap Sieving				0.72			
Coarse Aggregate Sieving		0.26	0.54	0.67	1.50		

FIGURE B-6

RATIOS OF F ACTUAL/F CRITICAL FOR
VARIOUS TEST PROCEDURES COMPARED WITH THE
M.T.C. TEST PROCEDURE FOR THE COARSE GRADED MATERIAL